Neutrinos Parallel Session—A Summary

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Abstract. We summarize the presentations on neutrino research made during the *Neutrinos* parallel sessions at CIPANP2003.

INTRODUCTION

The last ten years have seen an enormous growth of knowledge about neutrinos and their properties. We now have strong evidence for two different neutrino flavor oscillations, called "atmospheric" and "solar" oscillations after the sources of neutrinos with which these oscillations were first observed. Where neutrinos were once held to be massless, we now know they have small but finite mass. A consistent picture has emerged that explains these two oscillations in terms of an "MNSP" (Maki-Nakagawa-Suzuki-Pontecorvo) matrix, analogous to the CKM matrix in the quark sector. There are are two independent mass differences, Δm^2_{12} and Δm^2_{23}; three mixing angles θ_{ij}; and one CP phase δ_{CP}.

Even with all the progress in neutrino research in the last decade, our field is best defined by the questions that remain to be answered, so we organized our sessions accordingly. The atmospheric and solar neutrino oscillation parameters still have large uncertainties; these parameters will be measured much better in the next few years. The next round of neutrinoless double-beta decay measurements hope to answer several fundamental questions: What is the neutrino mass hierarchy? What is the absolute neutrino mass scale? Are neutrinos Dirac or Majorana particles? Future neutrino experiments will also attempt to measure the other MNSP matrix elements, θ_{13} and the CP phase δ_{CP}. Another open question is how to interpret the LSND [1] measurement, as it does not fit into the MNSP framework. The MiniBooNE [2] experiment will validate or contradict the LSND result. Several beyond-the-standard-model approaches have been proposed to incorporate LSND with the other two observed neutrino oscillations. Finally, high flux neutrino sources and improved detection techniques have allowed for high precision neutrino scattering measurements.

"SOLAR" NEUTRINO OSCILLATIONS: Δm^2_{12} AND θ_{12}

The biggest advances in our understanding of neutrino properties in recent years have come from measurements of the solar neutrino oscillations. Our sessions included pre-

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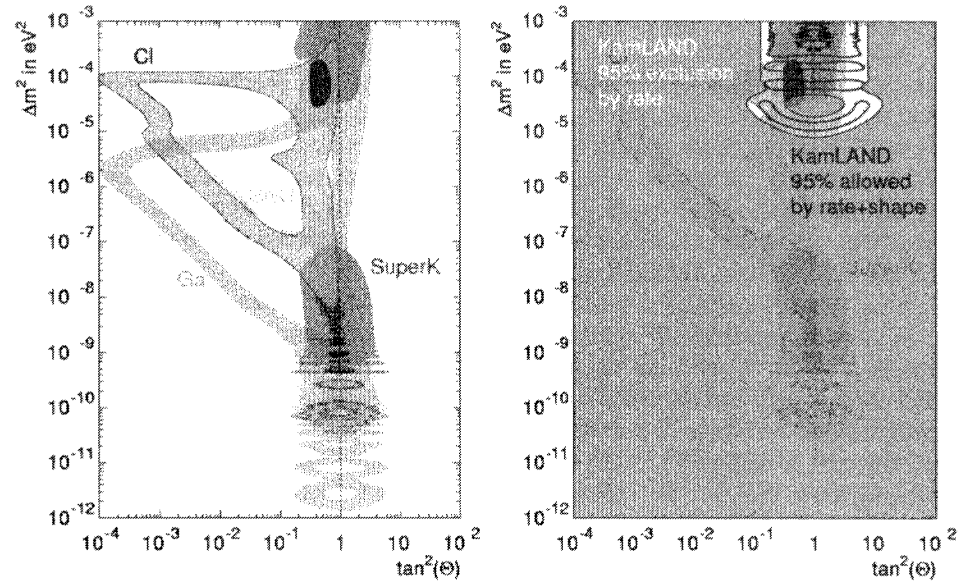

FIGURE 1. The constraints from "solar" neutrino oscillation experiments in Δm^2_{12}, $\tan^2\theta_{12}$ parameter space. The left plot shows the allowed regions from the gallium and chlorine radiochemical experiments, from Super-K, and from SNO, plus the allowed region from a combined fit to these experiments. The right plot overlays the additional constraints from the KamLAND rate and rate+shape analyses.

sentations of new measurements from the SNO [3] and KamLAND [4] collaborations that were published within the last year. Neil McCauley and John Orrell presented talks on SNO, while Bruce Berger spoke about KamLAND.

In the MNSP framework, the solar neutrino oscillation is that between ν_1 and ν_2. Radiochemical experiments with chlorine and gallium plus water-Čerenkov detectors like Super-Kamiokande [5] have all measured the deficit of solar ν_e's relative to the number expected from the SSM (solar standard model). The deficits measured in these experiments are consistent with a wide range of parameters in very different regions of Δm^2_{12}, θ_{12} parameter space.

SNO is also a water-Čerenkov detector, but it has a heavy water (D_20) target. It is sensitive to not only to ν_e's through charged-current (CC) interactions but also to the other neutrino flavors through elastic-scattering (ES) and neutral-current (NC) interactions. By measuring all three processes, SNO showed that the total neutrino flux, summed over flavors, is consistent with the SSM prediction. Furthermore, the results show an inferred 5.3σ appearance of $\nu_{\mu,\tau}$ in a ν_e beam, clear evidence for neutrino flavor change. The combination of the SNO results with the previous solar neutrino results rules out much of the previously-available oscillation parameter space, as shown in the left half of Figure 1.

KamLAND, by contrast, studies "solar" neutrino oscillations with a very different source: antineutrinos produced in nuclear power plants. KamLAND is located in a unique position in central Japan that allows the experiment to detect neutrinos produced by an ensemble of power plants. At a mean baseline of 180 km, the experiment detected $0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst})$ of the number of neutrinos expected if there were no oscillations. KamLAND is sensitive only to one of the previously-possible solar oscillation parameter regions, the so-called LMA (large mixing angle) region, so the KamLAND result rules out all the other solar oscillation solutions. A "shape" analysis of the energy dependence of the observed signal further constrains the LMA region. Some LMA parameters would have produced large shape distortions in the KamLAND data, but such distortions were not observed. The additional constraints due to the KamLAND results are shown in the right half of Figure 1.

Both SNO and KamLAND will provide additional measurements of the solar neutrino oscillation parameters in the next few years. SNO will measure the day/night flux asymmetry, which is sensitive to Δm^2_{12}, and the CC/NC ratio, sensitive to θ_{12}. KamLAND continues to add statistics to the reactor antineutrino measurement. With more data KamLAND will be able to make a much better Δm^2_{12} measurement, and it has some sensitivity to θ_{12}. Further down the road, a potential KamLAND solar phase could measure θ_{12} better with solar ^{7}Be neutrinos.

"ATMOSPHERIC" NEUTRINO OSCILLATIONS: Δm^2_{23} AND θ_{23}

In the MNSP framework, the atmospheric oscillation is that between ν_2 and ν_3. Cosmic-ray showers in the earth's atmosphere produce both ν_μ's and ν_e's; the ν_μ's oscillate as the neutrinos propagate through the earth, principally into ν_τ's. The best current measurement of atmospheric neutrino oscillations comes from Super-Kamiokande [5] measurements of both the ν_μ and ν_e flux as a function of zenith angle.

The "atmospheric" oscillation will be measured to higher precision with accelerator neutrinos by the MINOS [6] experiment, as described in a talk by Hugh Gallagher. MINOS will look for the appearance of ν_τ in a ν_μ beam. The neutrino beam will be produced at Fermilab with the NuMI beamline, while the MINOS experiment itself is located 735 kilometers away in the Soudan mine in northern Minnesota.

NEUTRINOLESS DOUBLE-BETA DECAY

We devoted a full session to the topic of neutrinoless double-beta decay. Rabi Mohapatra began with a theoretical introduction. Neutrinoless double-beta decay is possible if the neutrino is a Majorana rather than a Dirac fermion, in which case it is its own antiparticle. The decay rate depends on the absolute neutrino mass scale, or more precisely an effective mass $\langle m_{\beta\beta} \rangle$ that depends on all the neutrino masses and mixing angles—plus new Majorana phases. Thanks to this dependence, a measurement of neutrinoless double-beta decay could probe the neutrino mass hierarchy. However, under the "normal" mass hierarchy $m_1 < m_2 < m_3$, the phases can conspire to suppress $\langle m_{\beta\beta} \rangle$ such that a null result in the search for neutrinoless double-beta decay cannot rule out Majorana neutrinos.

Neutrinoless double-beta decay experiments face difficult challenges. The signal itself is tiny. The two-neutrino double-beta decay is a background, so good energy resolution is required to distinguish the neutrinoless double-beta decay peak at the endpoint of the two-neutrino spectrum. Backgrounds from natural radioactivity demand the use of very clean materials, while cosmogenic backgrounds require the experimental site to be underground. In addition, the necessary nuclear matrix elements are difficult to calculate.

Our sessions included talks on three neutrinoless double-beta decay projects that have chosen very different experimental techniques. Rick Norman described the CUORE [7] experiment, which will use a bolometric technique to search for decays of ^{130}Te in tellurium crystals having the natural 33.9% ^{130}Te abundance. A pilot program, Cuoricino, is already running at Gran Sasso. Albert Young described the Majorana [8] project, which will take advantage of the excellent energy resolution of germanium ionization detectors, a well-established technology. Majorana will search for neutrinoless double-beta decay of ^{76}Ge at 85% isotopic enrichment. Finally, Peter Rowson described the EXO [9] experiment, based on 80% enriched ^{136}Xe. EXO will use a liquid xenon TPC, and this ambitious experiment will attempt to extract and identify the barium daughter of the xenon decay on an event-by-event basis, a unique method to reject background.

FUTURE MEASUREMENTS OF MNSP ELEMENTS

Solar and atmospheric oscillations probe a subset of the MNSP matrix elements. They cannot determine the final two parameters, namely θ_{13} and the CP phase δ_{CP}. Our sessions included three talks on future projects to measure these parameters.

Karsten Heeger spoke about the possibility of measuring θ_{13} with nuclear reactors as a source. The CHOOZ [10] and Palo Verde [11] experiments saw no flux deficit to the 3% level at a baseline of 1 km, while KamLAND has seen a $39 \pm 12\%$ deficit due to the solar neutrino (θ_{12}) oscillation at a mean distance of 180 km. The θ_{13} oscillation should give a small subdominant oscillation in the $\overline{\nu}_e$ flux on top of the large θ_{12} oscillation as a function of distance. The absolute magnitude of this subdominant term depends on the unknown θ_{13}, but the locations of the maxima and minima depend on Δm^2_{13}, which can be inferred from the known solar and atmospheric Δm^2's. A two-detector experiment with systematic errors at the 1% level could either measure this subdominant oscillation or set much tighter limits on θ_{13}. This is a very interesting idea, and an experiment could be running within a few years. Groups in the US, Japan, Russia, and Europe are all actively pursuing this idea.

Adam Para presented a talk on the possibility of using a long-baseline off-axis neutrino beam to measure MNSP matrix elements. An off-axis NuMI beam could be used to provide a narrow-band 2 GeV beam for a $\nu_\mu \to \nu_e$ counting experiment. The probability for this oscillation depends on multiple parameters: both θ_{13} and δ_{CP}, but also on matter effects. Runs with both neutrino and antineutrino beams would give complementary measurements to partially resolve the parameter degeneracy. In addition, other experiments at different baseline distances, for example JPARC to Super-K, would also give complementary information.

Zohreh Parsa presented a very ambitious idea [12] for the ultimate neutrino oscillation experiment, one that could measure all MNSP parameters in a single ultra-long-baseline experiment. One proposal is a 2540 km baseline from Brookhaven to the Homestake mine in South Dakota, with a 500 kiloton water Čerenkov detector such as UNO [13]. An upgrade of the AGS to 1 MW is proposed to provide a wideband (.5–5 GeV) on-axis beam, aimed down into the ground. The ultra-long baseline provides oscillations versus energy across the beam energy spread, which allows the mixing angles to be measured well. In addition, the shape of the observed oscillation depends on both δ_{CP} and matter effects, so this experiment would also be sensitive to the CP phase and the neutrino mass hierarchy.

SHORT BASELINE OSCILLATION RESULTS AND THEIR IMPLICATIONS

In addition to the strong evidence for solar and atmospheric neutrino oscillations, there is also evidence for neutrino oscillations at shorter baselines from the LSND [1] experiment. This result implies oscillations at high Δm^2 and small mixing. Because of the large Δm^2, this signal, along with the solar and atmospheric oscillation interpretations, cannot be explained with the three standard model neutrinos.

The LSND experiment observed $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam created from muon decay at rest. This signal is typically interpreted via a neutrino oscillation model, but it could also be described by a rare lepton-number-violating μ^+ decay: $\mu^+ \rightarrow e^+\overline{\nu}\overline{\nu}_e$. Klaus Eitel from Karmen, another short baseline neutrino oscillation experiment, presented new results on a search for this μ^+ decay [14]. Karmen does not observe this signal and therefore rules it out as a possible explanation for the LSND result. Karmen is sensitive to some of the LSND neutrino oscillation signal, as is Bugey, at higher mixing, but there is still a substantial amount of the LSND allowed region which must be addressed.

The MiniBooNE experiment, presented by Terry Hart, is designed to confirm or rule out the entire LSND signal to 5σ [2]. It runs at higher energy and at a longer baseline than the LSND experiment to preserve the oscillation parameter L/E. MiniBooNE tests the signal in an independent way, with different detection techniques, different systematic errors, and different backgrounds. MiniBooNE began data taking in August of 2002, expects first results on ν_μ disappearance and cross sections by Fall 2003, and expects ν_e appearance results by 2005.

If the LSND signal is due to oscillations, there are several beyond the standard model theories which can accommodate LSND along with solar and atmospheric neutrino oscillations. Gabriela Barenboim presented one such theory in which CPT is violated in the neutrino sector [15]. In this case, the different neutrino and antineutrino mass spectra can reconcile all three signals. By tagging the neutrino sign in atmospheric oscillations, the MINOS experiment will be able to address this theory in the near future. The combined results of Borexino and SNO compared to KamLAND can also address this model. Likewise, the MiniBooNE experiment will also test this theory.

A number of beyond the standard model theories, such as GUT's, SUSY, and those involving large extra dimensions, predict the existence of sterile neutrinos which cannot interact via the weak interaction but can oscillate with the usual three neutrinos. Theories involving one sterile neutrino, invoked to accommodate all three oscillation signals, in either a 3+1 or a 2+2 mass hierarchy, are increasingly disfavored by the latest neutrino oscillation data. However, Michel Sorel presented recent work showing that a fifth neutrino in a 3+2 mass hierarchy opens possibilities for such sterile neutrino theories [16]. Upcoming ν_μ disappearance results from MiniBooNE and FINeSE [17] can directly address the mass hierarchy and what mixing parameters for these 3+2 models.

NEUTRINO SCATTERING PHYSICS

Intensive work in neutrino and accelerator physics over the last 30 years has led to high flux neutrino sources and much improved detection techniques. These advances have paved the way for a new generation of neutrino scattering physics experiments that probe other physics and contribute to understanding neutrinos.

M. Komatsu presented new results from CHORUS on charm hadron production measurements from νN deep inelastic scattering (DIS) interactions [18]. In the 1-20 GeV range there is rekindled interest in neutrino scattering physics in order to understand the DIS-to-resonance crossover region and to study nucleon structure at low Q^2. Eric Hawker gave an overview of low energy neutrino cross section data at these energies. Thia Keppel and Arie Bodek presented work on understanding the DIS-to-resonance region from charged lepton and neutrino scattering data [19]. These studies are crucial for the next generation of neutrino experiments that need good neutrino cross section models. Hugh Gallagher presented work on one such model called NEUGEN [20].

In addition to cross section measurements important as input for oscillation experiments, neutrino scattering can probe other physics. For example, neutrinos can pick out the strange spin of the nucleon, Δs, through measurement of the neutral weak current extrapolated to $Q^2 = 0$. Charged lepton experiments measuring Δs suffer from model dependence [21, 22], and the results from different experiments disagree even on the sign of Δs. Neutrino scattering cleanly picks out Δs and can provide an independent measurement. Morgan Wascko presented a soon-to-be-proposed experiment called FINeSE [17], designed to measure Δs at a near detector on the Fermilab Booster Neutrino Beamline. With a fine-grained detector followed by a muon range-out, FINeSE will also be able to measure neutrino cross sections to high precision and study ν_μ disappearance in conjunction with the MiniBooNE experiment.

Neutrino cross sections at even lower energies, in the tens of MeV, are of interest to solar oscillation experiments and astrophysics. Malcolm Butler discussed modeling of inelastic νN cross sections in these regions in order to understand ν-deuteron breakup reactions at SNO energies as well as pp fusion at threshold in the sun [23]. Measurements of these cross sections can be made at a high-precision low-energy neutrino scattering experiment at the Spallation Neutrino Source (SNS), presented by Bill Bugg [24]. SNS will be a copious source of neutrinos from muon decay at rest, allowing for cross section measurements crucial to astrophysics and nuclear theory.

CONCLUSIONS

This is an exciting period of neutrino physics, one in which new discoveries are being made rapidly. The field has changed dramatically in the three years since CIPANP2000, especially due to new measurements of solar neutrino oscillations. We expect many new results in the next three years, in time for CIPANP2006.

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